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INVESTIGATION OF HIGH TEMPERATURE THERMAL EXPANSION DEVICES
AND DESIGN OF A UNIT FOR USE WITH THERMAL IMAGE HEATING

Robert C. Folweiler

Lexington Laboratories, Inc.
35 Cambridge Parkway
Cambridge 42, Massachusetts

Contract No. AF19(628)-1616

FINAL REPORT

15 December 1962

Project 5634

Task 563401

Prepared for:

Electronics Research Directorate
Air Force Cambridge Research Laboratories

Office Of Aerospace Research
United States Air Force
Bedford, Massachusetts

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FOREWARD

This report was prepared by Lexington Laboratories, Inc., Cambridge, Massachusetts under USAF Contract No. AF 19(638)-1616, "Investigation of High Temperature Thermal Expansion Devices And Design of a Unit for Use With Thermal Image Heating". The work was administered by Electronic Systems Division, Air Force Systems Command, L. G. Hanscom Field, Bedford, Massachusetts.

Work on this contract was performed by R. C. Folweiler and W. B. Campbell under the supervision of W. D. Kingery.

ABSTRACT

Furnace enclosures have been studied that are to be used with a "double clamshell" arc imager. A design is presented for thermal expansion measurements using optical measuring techniques.

The unit is readily adaptable for other measurements, including electrical, kinetic and mechanical property measurements. A special advantage of the system is lack of added electrical and magnetic fields.

A maximum temperature well over 2000°C may be expected using two 5 KW Xenon arc sources.

The furnace may be placed within another enclosure to provide atmosphere control including vacuum.

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1.0 INTRODUCTION

Although much scientific and engineering interest has been devoted to imaging furnaces during the past decade, the areas of major effort have been design, efficiency, tracking or source control systems, reliable temperature measurement and high temperature melting. Relatively little effort has been directed toward the utilization of imaging systems to facilitate high temperature physical property measurements in the absence of impressed electric or magnetic fields. The failure to use imaging devices has resulted from several factors; including non-uniform heating, small heating volume and limited energy sources. In the present study, we have overcome these problems and have designed an image device for thermal expansion measurements at high temperatures.

Some thermal expansion measurements have been reported using thermal imaging. Chalmin¹ used a solar furnace and optical techniques as shown in Figure 1, to measure the expansion of MgO and ZrO₂ from room temperature to about 2000°C.

Other investigators^{2,3} have suggested techniques for property measurements, but no data have been reported in the literature. A furnace combining several features necessary for solar imaging has been constructed by Laszlo. It included provision for electrical contact, atmosphere control and specimen rotation for uniform heating. It is adaptable to thermal expansion measurements.

A major difference exists between solar imagers and the double clamshell imager⁴ under consideration here. The

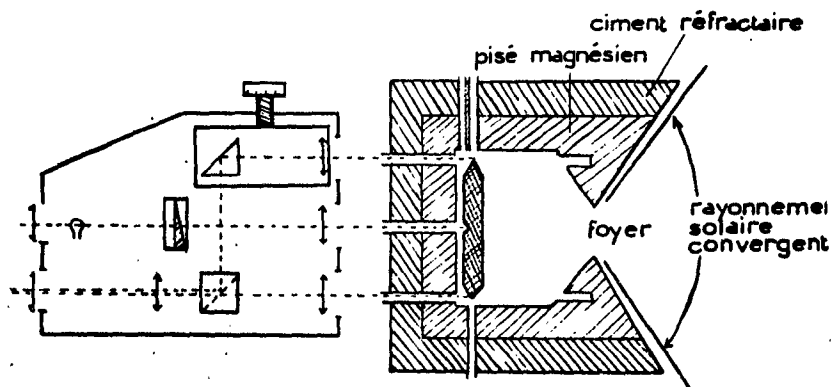


Fig. 2. - Four solaire dilatométrique, coupe horizontale.

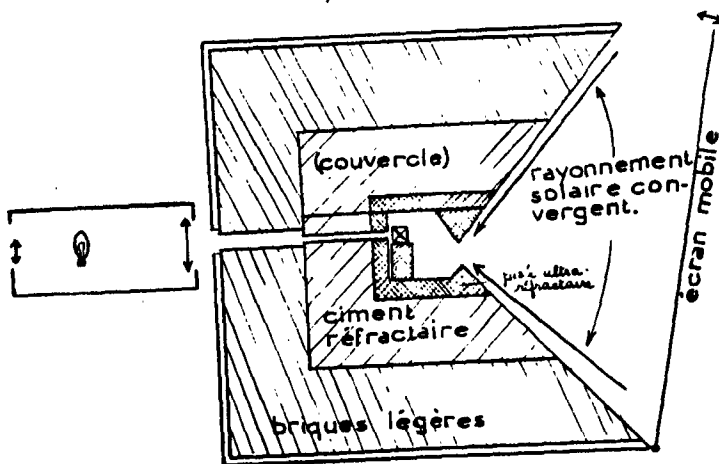


Fig. 2 bis. - Four solaire dilatométrique (coupe verticale).

Figure 1: Apparatus of M. R. Chalmers

solar imager irradiates the specimen from one side only over a cone with an angle of 140° for normal mirrors. The double clamshell has a similar cone of radiation, but from two sides, providing improved symmetry. By further enclosing the sample within a tubular chamber with reflecting and reradiating walls, reasonable temperature uniformity over a sample of moderate length may be attained.

2.0 FURNACE CONSTRUCTION

2.1 Experimental

Two furnaces were designed that were similar to Figure 5. Three concentric aluminum oxide tubes were used. The first model was 0.5 inches inside diameter, somewhat smaller than the source image. A second model was constructed using a 1.0 inch inside diameter tube.

A specimen, approximately one inch long, was cast around four thermocouples using a refractory alumina cement. (See Figure 2). The thermocouples were located in one half of the

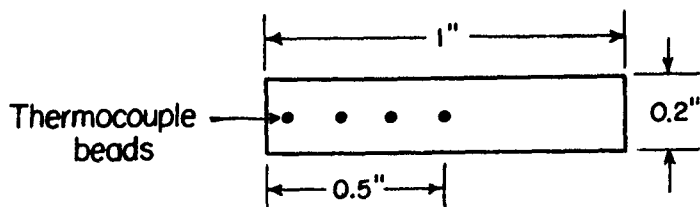


Figure 2: Drawing of Specimen showing location of thermocouples

specimen since the temperature gradient was expected to be symmetrical. The unit was placed in Cambridge Research Laboratory's double clamshell imager using two 1000 watt tungsten projector bulbs as sources. Figure 3 is a drawing of the basic system. The entire image, which was approximately 0.5 x 0.75 inches, entered the end of the furnace. Less than 33% of the energy is gathered by the imaging systems in the present configuration, and when the double reflection is considered, less than 20% of the 2000 watts input entered the furnace.

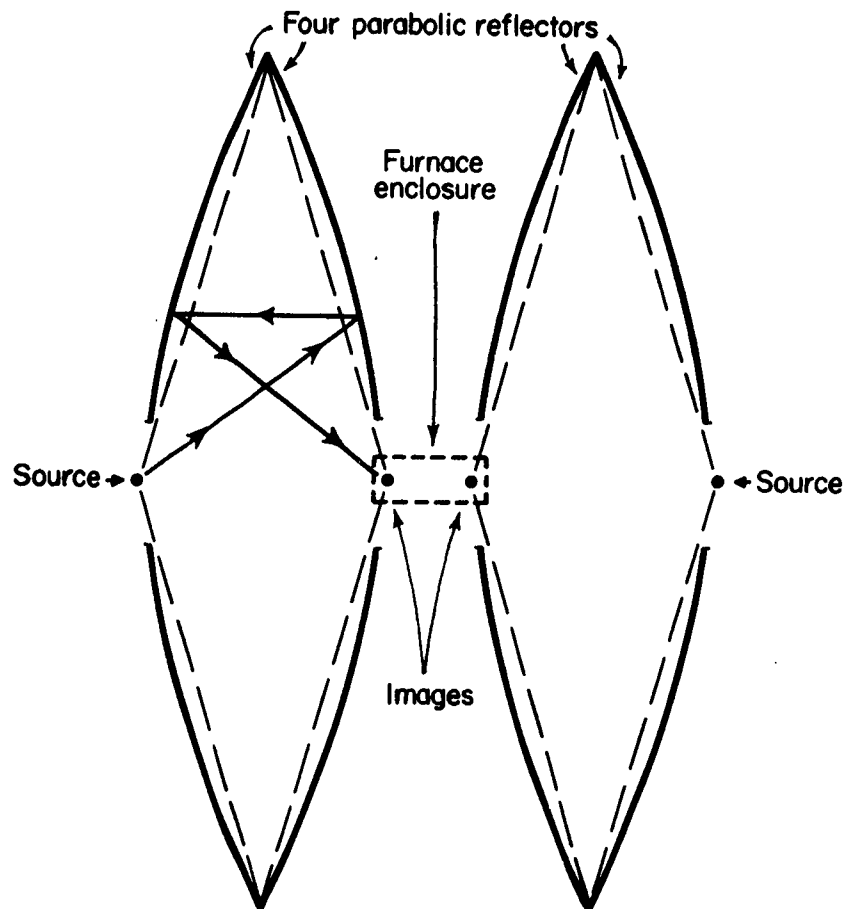


Figure 3: Double Clamshell Imager

The second furnace, six inches long, was intentionally much longer than necessary for containing the specimen in an effort to determine the optimum length for temperature uniformity. Temperature measurements in the specimen were made at the longest length (6"), with two inches removed (4"), and subsequently with another inch removed (3"). That is, temperature measurements were made at six, four, and three inch furnace lengths.

The temperature profiles at the two shorter lengths were similar, as seen in Figure 4, indicating a temperature difference of approximately 25°C at a specimen temperature of 620°C and 670°C for the four inch and three inch furnaces respectively. The gradient was less, 15°C , for the six inch furnace as might be expected because the greater length diffuses the temperature gradient.

2.2 Design

The furnace enclosure in which the specimen is placed is a critical portion of the equipment. It must be constructed to (a) provide ports to admit the radiant energy, (b) heat the specimen and (c) minimize heat losses while (d) permitting access for measurements.

The design that appears most promising is a tube type furnace, partially open at the ends with concentric radiation shields. Such a design is shown in Figure 5. This arrangement satisfies the above criteria.

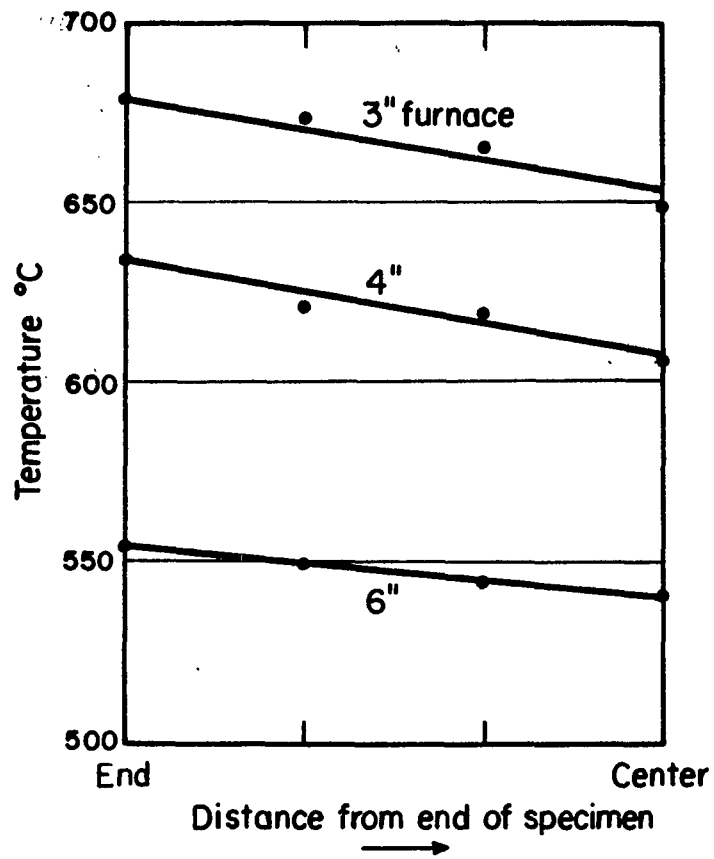


Figure 4: Temperature Profile In Specimen

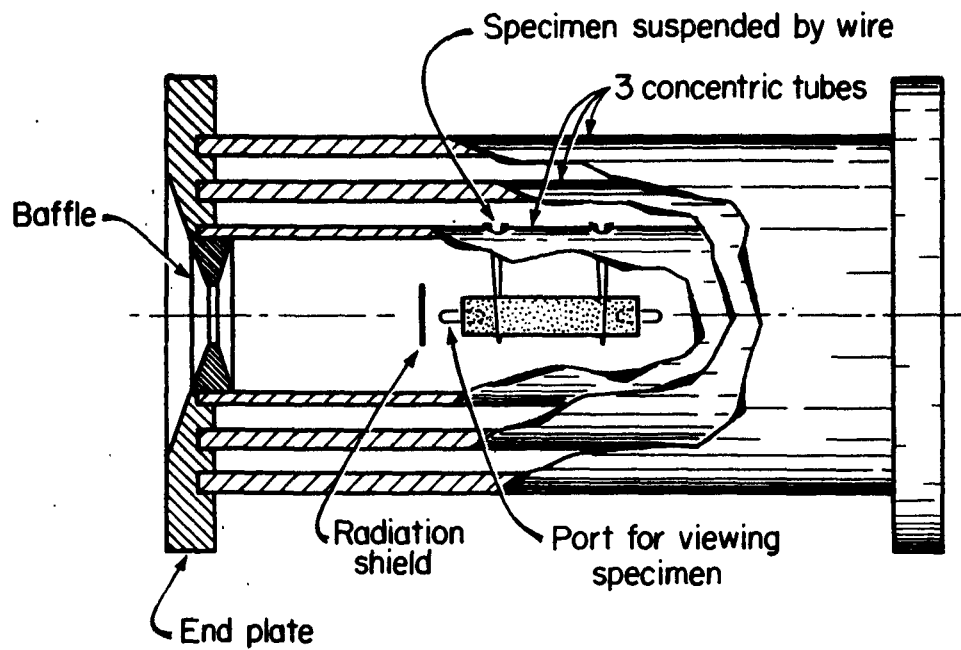


Figure 5: Furnace Construction

Several important aspects discovered in experimental testing and analysis (See Appendix) must be considered in the design. Contrary to most resistance furnace practice, the specimen was hotter at the ends than at the center. This results from impingement of the radiation mostly on the ends of the specimen. A much different gradient may be attained by making the inner wall of the furnace the energy source for the specimen so that the sides of the specimen receive the majority of the energy. Then the wall temperature determines the specimen temperature since the specimen is neither a source nor a sink.

The optics of the imaging system indicate that the most satisfactory design is to make the furnace length to diameter ratio less than three ($l/d < 3$). As illustrated in Figure 6, the walls of the furnace are fully irradiated by a fairly uniform flux (considering both sources). The ends of the specimen may be shielded from direct irradiation by a separate shield. The gradient may even reverse, with the ends being cooler. This may be easily adjusted by modifying the heat shield.

An acceptable gradient in the specimen would be 10°C , preferably less. The preceding design considerations indicate much lower gradients.

Ports are provided in the side for viewing the specimen with a filar telescope; permitting one to follow the thermal expansion of a specimen mounted as shown. The specimen is hung in the center by means of fine wires passing through holes in the side of the inner tube.

Excessive heat loss by reradiation and reflection would occur at the ends if no baffle were provided. Apertures, which are the side of the image, are placed in the end of the tube. This aperture blocks the unneeded area at the end of the tubes.

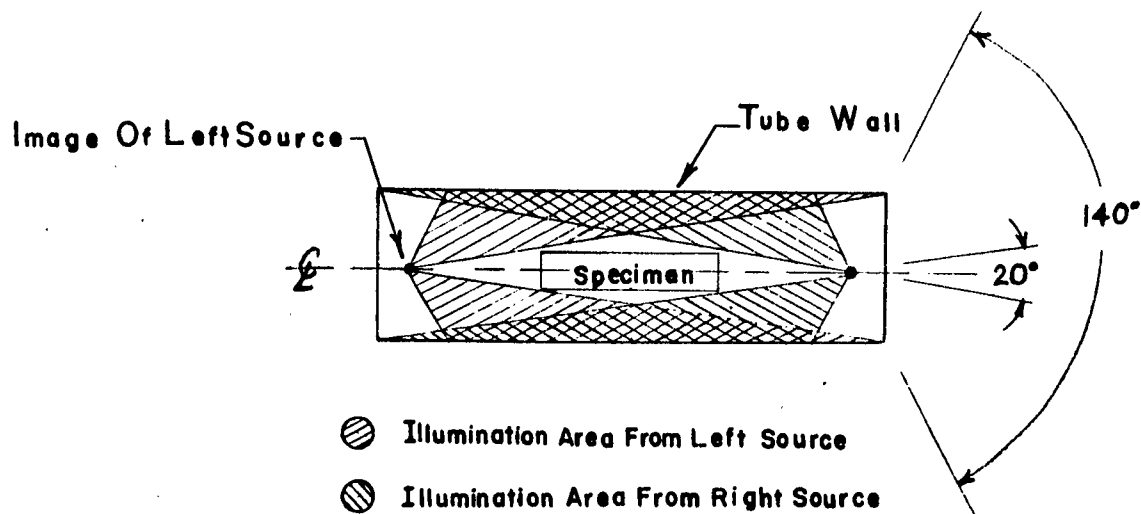


Figure 6: Flux distribution in Furnace

Not Drawn To Scale

2.3 Materials

A wide selection of materials is available for high temperature applications. The most important material properties which must be considered for the present application are radiative heat transfer, purity, and chemical and mechanical stability at high temperatures. Refractory metal stability is limited to reducing or vacuum atmospheres. Most metal oxides have excellent chemical and mechanical stability in a variety of atmospheres and have desirable heat transfer properties at elevated temperatures.

The most stable high temperature oxide available is ThO_2 . Thoria is available in fabricated shapes of high purity which are suitable for construction of critical furnace parts, including the inner tube, apertures and end plates. Material cost may be reduced by using other materials, in particular stabilized ZrO_2 and Al_2O_3 , for the outer heat shields.

At low temperatures, metals have higher thermal resistance than oxides and can be used effectively, atmosphere permitting. The use of metal for outer shields would increase the maximum temperature capability of the furnace.

Specimen hangers and end shields can be fabricated from refractory metal for reducing atmospheres or vacuum applications. For inert or oxidizing atmospheres small parts can be fabricated from noble metals such as rhodium and iridium.

3.0 THERMAL EXPANSION MEASUREMENTS

A number of standard techniques are available for measuring thermal expansion. The two most important ones are by dilatometry or optical measurements. The former enjoys general popularity because of adaptability. It is particularly applicable at temperatures up to 1000°C, the use limit of fused silica. Silica is appropriate because of its low coefficient of thermal expansion. Above this temperature other materials have been used, notably sapphire. Problems arise because of difficulties in cancelling out the high coefficient of expansion of sapphire. In any case, its use is limited to temperatures well below its melting point, 2015°C, because of dimensional instability and solid state reactivity. Refractory metals may be considered, such as tungsten and tantalum but these are limited to reducing or vacuum atmospheres because of their reactivity. Dimensional stability is again a problem.

Optical systems have problems that limit them to high temperatures and special applications; they are not readily adaptable to automatic recording devices and are often expensive. Working distance from the instrument to the specimen is limited. However, sufficiently long working distance equipment is available for applications in confined spaces which at high temperatures is easier to use than dilatometers. For the present application, optical systems are the most appropriate because of restricted working area, high temperatures, and the optical layout of the imager.

4.0 TEMPERATURE CAPABILITY

If one assumes a double clamshell imager using two 5 kW Xenon short arc lamps, an estimate may be made of the maximum temperature capability. The Xenon arc is transparent to its own radiation, so an auxiliary spherical reflector may be used to return energy to the system that would otherwise be lost through the back side of the lamp. By aluminizing the parabolic reflectors and overcoating with silicon monoxide, a reflectance of 90% can be obtained over a broad wavelength region. Knowing the collection angle for the optical system, the maximum calculated energy reaching the desired image area would be slightly over 50% of the input, or a total of 1200 cal/sec over two areas of approximately 0.35 cm^2 each. These values compare favorably with powers available with a 60 inch solar imager.

Using Christensen's radiation heat transfer equation⁵ for concentric spheres or cylinders, and assuming only radial heat flow in the cylinder, a single tube as a heat shield will permit an enclosure temperature of 2300°K . Obviously, energy will be lost out the ends, but the addition of multiple concentric heat shields and baffles at the ends should alleviate this loss.

5.0 SUMMARY

A furnace has been designed that will permit measurement of thermal expansion. By appropriate baffles within the furnace a negligible temperature gradient in the sample can be attained. Minor changes in construction would permit other high temperature properties to be measured.

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APPENDIX

Estimation of Temperature Profile In Specimen Centered In Furnace

1) INTRODUCTION

In order to approach this problem analytically, a number of simplifying assumptions must be made. Primarily, these involve selection of geometrical approximations and temperature distribution of parts of the system. In several case, only ranges may be calculated, from which one may deduce or estimate a balance of variables. Equations, several factors and the following notation were taken from McAdams: Heat Transmission, Third Edition:

q = Heat Flux

ϵ = Emissivity

T = Absolute Temperature

A = Area

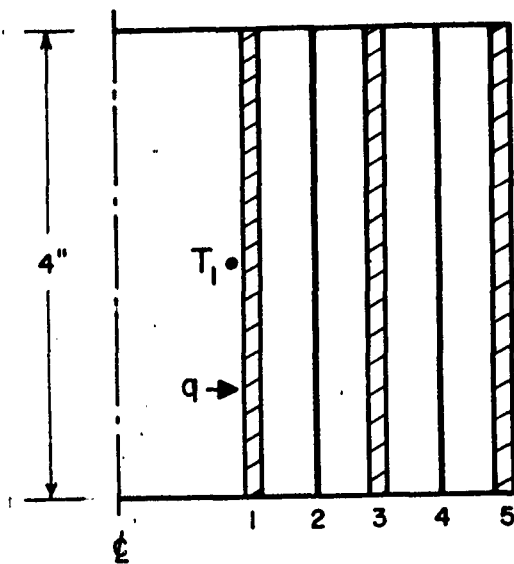
σ = Stefan-Boltzmann Constant

f = Factor involving emissivity and reradiation

F = View factor

2) TOTAL RADIATION RESISTANCE OF FURNACE

The total radial heat leakage through the walls may be calculated easily by assuming an inner wall temperature, in this case 500°C or 1390°R .



Walls 1,3,5
Al₂O₃ $\epsilon = 0.4$

Walls 2,4
Al sheet $\epsilon = 0.1$

$$q = \sigma A f_e (T_1^4 - T_2^4)$$

$$T_1^4 - T_2^4 = T_2^4 - T_3^4 = T_3^4 - T_4^4 = T_4^4 - T_5^4 = \frac{q}{\sigma A f_e}$$

$$T_5^4 - T_6^4 = \frac{q}{\sigma A_o \epsilon}$$

$$T_1^4 - T_6^4 = \frac{4q}{\sigma A f_e} + \frac{q}{\sigma A_o \epsilon}$$

The factor f_e may be calculated by using the emissivities of the two materials and assuming the concentric cylinders have equal areas:

$$\epsilon_{Al} = 0.1 \quad \epsilon_{Al_2O_3} = 0.4$$

$$\frac{1}{f_e} = \left(\frac{1}{0.1} - 1\right) + \left(\frac{1}{0.4} - 1\right) + 1 = 11.5$$

$$\text{Thus, } q = \frac{f_e \approx 0.1 \sigma (T_1^4 - T_6^4)}{\frac{40}{A} + \frac{2.5}{A_o}}$$

Take the average diameter to be $D = 2$ inches and the sink diameter $D_o = 3$ inches, then

$$q = 7.7 \text{ watts}$$

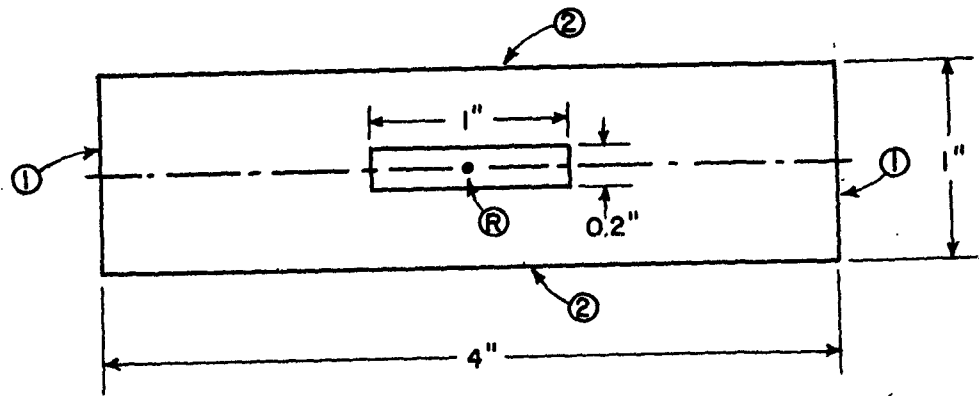
If there were just one wall made of Al_2O_3 .

$$q = 64 \text{ watts.}$$

Conduction and convection in the system would be effective at these lower temperatures, tending to increase the heat loss.

3) Specimen Temperature,

In this section and future parts, the following configuration is assumed:



The ends of the cylinder (1) are radiant sources (2) is the wall, a sink and (R) is the specimen. View factors may be calculated between the source, sink and specimen surfaces. The factors are $F_{R1} = 0.04$ and $F_{R2} = 0.96$. Similarly $F_{12} = 0.9$.

$$q_{12} = \sigma A_1 f_{12} (T_1^4 - T_2^4)$$

$$\frac{1}{A_1 f_{12}} = \frac{1}{A_1} \left(\frac{1}{\epsilon} - 1 \right) + \frac{1}{A_2} \left(\frac{1}{\epsilon} - 1 \right) + \frac{1}{A_1 F_{12}}$$

$$\frac{A_1}{A_2} = 0.125 \text{ Thus, } f_{12} = 0.36$$

$$T_1^4 = T_2^4 + \frac{q_{12}}{\sigma A_1 f_{12}}$$

$$T_2^4 = 1390R.$$

If $q_{12} = 30 \text{ BTU/hr}$

then: $T_1 = 1690 \text{ R}$

If $q_{12} = 60$ BTU/hr (18 watts)

Then: $T_1 = 1890$ R

4) Specimen Temperature Gradient

$$T_R^4 = \frac{a T_1^4 + a T_2^4}{a + b}$$

By making appropriate calculations for a & b (See reference for definition), $T_R = 1450$ R.

5) Specimen Gradient

If T_e = temperature of end of specimen
and

T_c = temperature of end center of specimen

Then (from Carslaw and Jaeger Conduction of Heat In Solids, 1954)

$$\frac{T_e - T_c}{T_e - T_2} = 1 - \frac{l}{\cosh l \sqrt{\frac{2h}{Tk}}}$$

where l = Specimen half length

and $h = 40\sigma\epsilon T^3$

If $\epsilon = 0.4$ and $T = 1390$ R

then:

$$\frac{T_e - T_c}{T_e - T_2} = 0.3.$$

$$\text{Thus } T_e - T_c = 18^\circ\text{R}$$

which is the temperature difference between the end and the center of the specimen.

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| AD AF Cambridge Research Laboratories, Electronic Research Directorate, Bedford Massachusetts INVESTIGATION OF HIGH TEMPERATURE THERMAL EXPANSION DEVICES AND DESIGN OF A UNIT FOR USE WITH THERMAL IMAGE HEATING, by R. C. Folweiler. December 1962. 21p. incl. illus. Proj. 5634; Task 563401 (AFCRL-62-952) Unclassified Report Furnace enclosures have been studied that are to be used with a "double clamshell" arc imager. A design is presented for thermal expansion measurements using opti- cal measuring techniques. The unit is readily adaptable for other measurements, including electrical, kinetic and mechanical property measurements. | UNCLASSIFIED 1. Thermal Imaging 2. Thermal Expansion 3. High Temperature 4. Property Measure- ments 5. Furnace Design I. Contract No. AF19 (628)-1616 II. OAR Project 5634, Task 563401 III. Lexington Labora- tories, Inc., Cambridge, Mass. IV. R.C.Folweiler | AD AF Cambridge Research Laboratories, Electronic Research Directorate, Bedford Massachusetts INVESTIGATION OF HIGH TEMPERATURE THERMAL EXPANSION DEVICES AND DESIGN OF A UNIT FOR USE WITH THERMAL IMAGE HEATING, by R. C. Folweiler. December 1962. 21p. incl. illus. Proj. 5634; Task 563401 (AFCRL-62-952) Unclassified Report Furnace enclosures have been studied that are to be used with a "double clamshell" arc imager. A design is presented for thermal expansion measurements using opti- cal measuring techniques. The unit is readily adaptable for other measurements, including electrical, kinetic and mechanical property measurements. | UNCLASSIFIED 1. Thermal Imaging 2. Thermal Expansion 3. High Temperature 4. Property Measure- ments 5. Furnace Design I. Contract No. AF19 (628)-1616 II. OAR Project 5634, Task 563401 III. Lexington Labora- tories, Inc., Cambridge, Mass. IV. R.C.Folweiler | UNCLASSIFIED 1. Thermal Imaging 2. Thermal Expansion 3. High Temperature 4. Property Measure- ments 5. Furnace Design I. Contract No. AF19 (628)-1616 II. OAR Project 5634, Task 563401 III. Lexington Labora- tories, Inc., Cambridge, Mass. IV. R.C.Folweiler |
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